Imaging in Geospace White Paper

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Participants: Laila Andersson, Pontus Brandt, Hugh Christian, Bob Clauer, Eric Donovan, Matt Fillingim, Nicky Fox, Steve Fuselier, Dennis Gallagher, Glynn Germany, Jerry Goldstein, Jim Green, Mike Henderson, Tom Immel, Marc Lessard, Kan Liou, Dirk Lummerzheim, Stephen Mende, Ching Meng, Don Mitchell, Dan Morrison, George Parks, Joe Perez, Craig Pollock, Bill Sandel, John Sigwarth, Jim Spann.

Imaging is crucial to understanding the complex interacting set of systems that make up the Sun Solar System. The accessibility of Geospace renders it the ideal laboratory to explore and understand plasma processes that are ubiquitous in the Sun-Solar System and indeed throughout the Universe. It is also a complex, coupled system in which there are dynamic linkages between diverse plasma regimes. Understanding this complex interrelationship, on spatial scales ranging from small to global, is impossible without global imaging. Imaging is the only way to fully observe and understand the complex way that these diverse systems interact. Two compelling themes emerge in the context of how imaging in Geospace relates to exploring the evolution and destiny of planetary atmospheres/magnetospheres. These are (1) the coupling between diverse plasma regimes from the solar wind to the atmosphere, (2) the acceleration of particles and the associated energy transfer.

Two, of many, examples:

(1) The solar wind variations drive planetary magnetospheres which in turn are intimately connected to the ionosphere and atmosphere. Radio tomography can provide information about how the solar wind and magnetosphere is coupled, while global EUV/FUV/ENA observations enable the connection between the magnetosphere, ionosphere and atmosphere to be made. Earth's thermosphere is the closest laboratory which most resembles the Martian surface. Imaging the ionosphere-thermosphere region using an FUV imager will allow us to fully characterize the thermospheric structure and variations. This will lead to more accurate global thermosphere circulation models which will be applicable to Mars and vital for calculations of aerocapture and aerobraking and provide insight into how the Mars atmosphere came to be and what it may become.

(2) Imaging plays a major role in one of the key issues for the Sun-Solar System Connections that of particle acceleration and energy transfer. Observations of multiscale auroral dynamics and ring current variations, using FUV and ENA techniques with in situ particle and field measurements, will provide an understanding of the acceleration and energy transfer mechanism. This will allow us to extend our understanding at Earth to other planets and interplanetary space.

Imaging themes and top priorities are identified in Geospace Imaging Exploration Matrix.

Imaging provides more information than any practical number of single-point measurements. It is crucial to understand the complex interacting set of systems that make up Geospace if we are to have properly constrained and accurate predictive models that are critical to support exploration, including a sustained human presence in space. This is particularly applicable to exploring the origin and evolution of planetary atmospheres and magnetospheres. Promising and innovative techniques are being developed to image to Geospace and other planetary systems. The four primary tools used to image Geospace are Energetic Neutral Atom (ENA), Radio Tomography, and Photon Imaging, that includes x-ray, extreme ultraviolet (EUV), far ultraviolet (FUV), visible (VIS) and infrared (IR).

ENA Imaging

Energetic Neutral Atom (ENA) imaging has emerged as a powerful tool for remotely sensing space plasma and thus has opened a window to a previously invisible region of space. ENA imaging relies on detecting neutral particles, rather than photons, and is capable of imaging any singly charged ionic plasma.

ENA imaging is thus far applied to study the magnetospheres of Earth, Jupiter, and Saturn. Future applications include these and also the study of solar processes, the magnetosphere of Mercury, and the global knowledge of the very boundaries of our solar system. ENA imaging across the energy spectrum probing plasma processes remotely and in a spatially synoptic fashion, providing pictures of how large-scale plasma systems manifest themselves and interact with other plasma systems that either are contiguous or spatially co-existent.

The development of robust compositional discrimination will enrich the technique by enabling species dependent processes to be studied, such as atmospheric escape to space. Extension of the energy range, improved angular resolution and photon rejection techniques will enable the retrieval of the plasma pressure, which plays a central role in space plasma physics.

FUV imaging

Far Ultraviolet (FUV) imaging of planetary upper atmospheres in conjunction with other in-situ and remote measurements are required to solve many outstanding issues directly related to the exploration of the Solar System. FUV images can be used to obtain a direct measure of changes in the composition of the thermosphere on a planetary scale as well as the conductivity of the ionosphere both at auroral latitudes and at low-to-mid latitudes.

The remotely observed changes in composition provide multiple constraints on thermospheric planetary circulation models that can be applied to planetary atmospheres including those of Mars and Jupiter. The ionospheric conductivity impacts the dynamics of the plasmasphere and ring current that lead to the formation of the radiation belts through the interaction with electric fields. Multispectral observations in the FUV provide the data to determine ionospheric conductivity. Energetic protons and other precipitating ions (e.g. He and O) are relatively little affected by electric fields and therefore are reliable tracers of terrestrial and planetary magnetospheric particle regions. The application of far ultraviolet (FUV) imaging to planetary atmospheres is critical for understanding the ionosphere, thermosphere and magnetosphere systems across our solar system and indeed plasma acceleration in the sun and throughout the universe.

Development of hyperspectral detectors with greater sensitivity will provide the necessary tools to advance our understanding and explore planetary atmospheres beyond Earth.

EUV Imaging

EUV imaging allows us to obtain a global view of space plasmas. At the Sun, EUV imaging lets us witness the explosive, dynamic physics of solar flares and coronal mass ejections. In Geospace, EUV imaging of Helium ions has dramatically improved our physical understanding of the Earth's inner magnetosphere, and demonstrated that global monitoring of the plasmasphere is a critical tool for understanding magnetospheric dynamics. We now have a very reliable basic picture of the global evolution of Earth's plasmasphere during and following storms, so that we can use EUV plasmasphere images to diagnose space weather and predict changes in the Earth's radiation belts that can pose a health hazard to astronauts and a threat to space hardware. Understanding of the basic plasma physics of Geospace, obtained by ultraviolet imaging, will continue to be critically important and relevant as we further explore the Solar System. Inference of global electric fields from plasma motions is made possible with EUV imaging, a crucial new capability. We can use EUV imaging of Sulfur ions to learn more about the Io plasma torus in Jupiter's magnetosphere. Saturn's inner magnetosphere, which is subject to many of the same physical phenomena as Earth's quiet-time plasmasphere, can also be imaged in EUV. Advances in mirror performance and filter rejection will open up new views of plasma imaging. In short, the global perspective provided by EUV imaging will be an essential and indispensable part of future space exploration.

X-ray Imaging

Auroral x-ray imaging provides an important adjunct to auroral imaging at longer wavelengths. X-rays provide unique insights into the sources, distribution, and transport of multi-keV electrons in the magnetosphere. As recent missions have demonstrated, the local time and intensity distributions of auroral x-rays differ significantly from auroral emissions in the UV and visible ranges. The relationship between the energies of auroral x-rays and the electrons that produce them differ from those of the UV and visible emissions in ways that make x-ray imaging highly complementary to them.

The fundamental challenges of auroral x-ray imaging are how to achieve sufficient sensitivity while maintaining sufficient angular resolution. The wide field of view of the auroral zone coupled with the relatively high x-ray energy strongly disfavors imaging techniques based on grazing-incidence mirrors. Favored imaging methods are therefore based on some form of coded-aperture or generalized pinhole camera method, coupled with single-photon counting and energy analysis to measure the auroral x-ray spectra. All of these techniques will benefit from large-area (>100 cm^2 to >1000 cm^2), energy-resolving (E/dE > 5) detector arrays with low-noise readouts for x-ray spectroscopy consistent with the detector energy resolution. These instruments also will benefit from advances in reducing the mass and power and increasing the radiation tolerance of space flight digital and sensor analog electronics, as well as improvements in on-board processing and data-handling capabilities.

Visible and Infrared Imaging

Temporal variations in visible auroral shapes and luminosity in the Earth's ionosphere vary from tens of minutes to small fractions of a second (~100 Hz). Spatially, features with scale sizes smaller than 1 km and as large as a few hundred km are routinely observed simultaneously. On global scales, conjugacy of auroral forms is important because it represents corresponding dynamics in the magnetotail and plasma sheet or the cusp regions. The visible dayglow and nightglow has successfully been used to infer global mesospheric/lower thermospheric winds and temperature from the O2 atmospheric bands as well as small-scale wave properties from the O and OH nightglow. Infrared and visible wavelengths are used to infer cloud properties and aerosol concentrations in the Earth's atmosphere, important parameters for climate studies. Infrared imaging has increased significance to the upper atmosphere of Mars both because of the CO2 atmosphere and the highly dynamic and important aerosol forcing.

Developments needed to support these observations include improvements in low-light imaging technology, increases in telemetry bandwidth, and improvements in lossless compression techniques. For aeronomy, the next generation technique would be spaceborne instruments with high spectral resolution coupled with 2D-imaging capability. Simultaneous auroral observations in opposite hemispheres are important in that they enable conjugacy studies.

Radio Imaging

There are three major techniques for radio imaging; radio sounding, radio tomography, and radio interferometery. Radio sounding and tomography use active wave generation and reception to obtain 2-dimensional electron density images to very low values (~0.01 cm^{-3}). Imaging low-density plasma is difficult with normal techniques but these measurements can be made from 10s of seconds to 10s of minutes and consequently produce images of magnetospheric dynamics, plasma loading, and evolution of regions and boundaries. Radio sounding can be accomplished with one satellite, such as that implemented on the IMAGE spacecraft but radio tomography must utilize a constellation of spacecraft. Radio tomography is based on well-known methods using simple antennas and radio waves. The total electron contents are measured through the delay of radio signals between transmitters and receivers. This is a highly accurate measurement and has been used by astronomers for long time to find information about the interstellar medium. A density image can then be derived through tomography of multiple radio signals that has passed through a common space volume, which in the same way as tomography is used in medicine today. The third technique; radio interferometery, utilizes aperture synthesis techniques to produce images of radio sources. Natural wave emissions are sites of either plasma instabilities or wave-particle interactions that are tracers for a number of important energy transfer processes. Radio interferometry can be used to obtain 2-dimensional images of radio sources such as Type III, Type IV solar bursts, auroral kilometric radiation, and many others. Topologies of interacting CME's, and the evolution of solar wind structures and Space weather predictions using radio imaging are among the key science targets.

Developments that are needed are focused on multiple spacecraft system technology.